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Research Article

Ceres: Astrobiological Target and Possible Ocean World

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Abstract

Ceres, the most water-rich body in the inner solar system after Earth, has recently been recognized to have astrobiological importance. Chemical and physical measurements obtained by the Dawn mission enabled the quantification of key parameters, which helped to constrain the habitability of the inner solar system's only dwarf planet. The surface chemistry and internal structure of Ceres testify to a protracted history of reactions between liquid water, rock, and likely organic compounds. We review the clues on chemical composition, temperature, and prospects for long-term occurrence of liquid and chemical gradients. Comparisons with giant planet satellites indicate similarities both from a chemical evolution standpoint and in the physical mechanisms driving Ceres' internal evolution. Key Words: Ceres—Ocean world—Astrobiology—Dawn mission. Astrobiology 20, xxx–xxx.

1. Introduction

Large water-rich bodies, such as the icy moons, are believed to have hosted deep oceans for at least part of their histories and possibly until present (*e.g.*, Consolmagno and Lewis, 1978). Their rock phase was predicted to be subject to extensive aqueous alteration leading to a hydrated mantle with carbonaceous chondrite-like composition (*e.g.*, Ransford *et al.*, 1981). The existence of oceans has been confirmed at many such moons, for example, Europa (Khurana *et al.*, 2004), Ganymede (Kivelson *et al.*, 2002), Enceladus (Iess *et al.*, 2014), and Titan (Iess *et al.*, 2012). Similarly, deep oceans have been proposed to occur in dwarf planets based on geophysical grounds (*e.g.*, McCord and Sotin, 2005; Desch and Neveu, 2017).

Observations by recent missions (New Horizons for Pluto and Dawn for Ceres) support these geophysical models [*e.g.*, Nimmo *et al.* (2016) for Pluto and references in this article for Ceres]. The prospect for long-lived oceans is a key component in the assessment of the habitability potential of these bodies, that is, their potential to produce and maintain an environment favorable to life. The purpose of this article is to assess Ceres' habitability potential along the same lines and use observational constraints returned by the Dawn mission and theoretical considerations.

Ceres comprises nearly one-third of the mass of the asteroid belt. Its mean radius and bulk density, respectively, 470 km and 2162 kg m^{-3} (Russell *et al.*, 2016), are intermediate between Enceladus (252 km and 1611 kg m^{-3}) and Europa (1560 km and 3014 kg m^{-3}), and comparable with those of many other icy moons and icy dwarf planets in the solar system. Ceres shares spectral similarities with C-type asteroids, in particular with Hygiea (Rivkin *et al.*, 2019) and 324 Bamberga (Takir and Emery, 2012). However, as per its outstanding properties, Ceres is more akin to icy satellites than to asteroids, in particular based on its large bulk water content and large size. McCord and Sotin (2005) pointed out that Ceres contains the right amount of both water and rock for sustained heating, resulting in the formation of a volatile-rich shell. This was supported by the early detection

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of hydrated materials on Ceres' surface (Lebofsky, 1978), suggesting pervasive aqueous alteration (Rivkin and Volquardsen, 2009).

While Ceres does not experience tidal heating, it is sufficiently close to the Sun and contains long-lived radioisotopes ($\sim$73 wt % rock) to potentially preserve brines until present (Castillo-Rogez and McCord, 2010) and meet conditions favorable for brine volcanism (Kargel, 1991). The prospect for Ceres to maintain mild interior temperatures throughout its history is quantified by thermal modeling. Castillo-Rogez and McCord (2010) found that Ceres' ice-rich shell could host temperatures as warm as 240 K a few tens of kilometers deep for most of its history. This led Castillo-Rogez and Lunine (2012) to propose that Ceres could be of astrobiological interest. A brief review of the pre-Dawn state of knowledge pertaining to Ceres' geophysics and chemistry is summarized in Section 2.

Dawn was the first mission to perform near-global geological, chemical, and geophysical mapping of an ice-rich body via mapping with multispectral imager (Framing Camera, Sierks *et al.*, 2011), visible and infrared spectrometer (VIR) (De Sanctis *et al.*, 2011), gamma ray and neutron detector (GRaND) (Prettyman *et al.*, 2011), radio science (Konopliv *et al.*, 2011), and stereoimaging for topography mapping (Park *et al.*, 2019). Observational campaigns for more than 3 years have made Ceres one of the best explored ice-rich bodies. These observations have revealed extensive chemical and geological activity, likely until very recent times, when the age of Occator's bright spots (called faculae) is considered. The data also suggest the presence of liquid inside Ceres through time, perhaps in the form of pore fluid in a silicate matrix or as a confined relict brine (or brine pockets).

Finally, Dawn revealed the presence of abundant carbon in Ceres' regolith (Prettyman *et al.*, 2017; Marchi *et al.*, 2018), as well as localized spots rich in organic matter (*e.g.*, De Sanctis *et al.*, 2017). Altogether, these observations not only confirm but also emphasize the astrobiological significance of Ceres. Key findings from the Dawn mission are summarized in Section 3. We assess the astrobiological implications of these observations and whether or not conditions within Ceres could have produced habitable environments and are amenable to advanced prebiotic chemistry in Section 4. We conclude that Ceres is a candidate ocean world according to the definition set forth in the Roadmap for Ocean Worlds (ROW) (Hendrix *et al.*, 2019).

2. Pre-Dawn Assessment of Ceres' Geophysical State

In this section, we briefly review expectations on Ceres' internal evolution ahead of Dawn's arrival. Available physical properties indicated that Ceres would be an evolved, internally differentiated body with a high prospect for preserving liquid until present. This section is by no means exhaustive and a more detailed review on the topic can be found in McCord and Castillo-Rogez (2018).

Ceres' bulk density was long known to be $\sim$2100 kg m^{-3} (see review by McCord and Sotin, 2005), intermediate between the values for water ice and silicates. This corresponds to a bulk fraction of water much higher than terrestrial planets and most rocky asteroids (27 wt % free water, *i.e.*, not bound to minerals, McCord and Sotin, 2005). This suggests Ceres is more akin to other icy moons and dwarf planets of the outer solar system. Ceres is likely not unique in the main belt: at least one body, 10 Hygiea, and shares similar spectral properties (*e.g.*, Vernazza *et al.*, 2017; Rivkin *et al.*, 2019) and density ($\sim$2000 g/cm^3) (Vernazza *et al.*, 2019).

Using the shape data of Carry *et al.* (2008), Zolotov (2009) concluded that Ceres has an undifferentiated porous interior structure. However, thermal evolution models of Ceres, using shape data derived from telescopic observations (*e.g.*, Thomas *et al.*, 2005; Carry *et al.*, 2008; Drummond *et al.*, 2014), indicate that, following accretion, the dwarf planet could have differentiated into a silicate core and a water-rich outer layer. These models suggest that Ceres could have harbored a global subsurface ocean for several hundred million years after its formation (*e.g.*, McCord and Sotin, 2005; Castillo-Rogez and McCord, 2010). Even though these studies used reference average surface temperatures 180–200 K instead of the current best estimate of 155 K at the equator (Hayne and Aharonson, 2015), the prospect remains that salt eutectic temperatures could be attained at relatively shallow depths and persist for an extended period of time.

A major difference between Ceres and other large main belt asteroids is the absence of an asteroid family, which Rivkin *et al.* (2014) interpreted as potentially due to an ice-dominated shell whose ejecta would vanish as a result of ice sublimation. An ice-dominated shell was predicted by geophysical modeling. Conversely, the large families associated with 10 Hygiea and 24 Themis have been interpreted as evidence for the preservation of a thick undifferentiated ice/rock crust at these bodies (Rivkin *et al.*, 2014).

Recent models with more elaborate physics explored a greater parameter space to address Ceres' potential for both hydrothermal activity and subsolidus convective transport in a thick ice shell (Neumann *et al.*, 2015; Neveu *et al.*, 2015; Travis *et al.*, 2015; Bland and Travis, 2017). Some studies accounted for the presence of salts leached from accreted silicates following hydrothermal processing, the latter of which is inferred from Ceres' pervasively hydrated surface (Rivkin *et al.*, 2006; Castillo-Rogez and Young, 2017). Thermal evolution models consistently yield temperatures in Ceres' shell that could remain above the eutectic temperature of relevant salts (>220 K, *e.g.*, for chloride mixtures) until present. Therefore, modeling studies predict that pockets of concentrated brines could exist at the base of the crust today (>50 km deep in Castillo-Rogez and McCord, 2010; Castillo-Rogez and Lunine, 2012; Neumann *et al.*, 2015; Neveu *et al.*, 2015).

However, the extent of these pockets was poorly understood by lack of constraints on Ceres' composition and geophysical properties. Modeling of heat transfer in a ''mud ball'' even suggested that an $\sim$300-km radius ocean loaded with silicate fines (<10 s of microns) could remain until present (Neveu and Desch, 2015; Travis *et al.*, 2015). Although not specific to Ceres, Kargel (1991) predicted that brines produced by aqueous alteration of the silicates could drive volcanic activity in large asteroids. It is remarkable that most pre-Dawn models of Ceres' thermal evolution predicted the long-term preservation of a liquid layer despite using different assumptions on the modalities of heat transfer.

3. Post-Dawn State of Knowledge of Ceres

In this section, we report observational evidence available from the Dawn observations for the abundance of volatiles (Section 3.1), evidence for an evolved interior (Section 3.2), rich chemical composition (Section 3.3), and hints for recent geological activity (Section 3.4) on Ceres. Salient lines of evidence for the habitability of Ceres from mineralogical, elemental, geological, and geophysical observations are shown in Fig. 1.

3.1. An ice-rich world

Measurements of hydrogen by GRaND indicate the presence of a global, subsurface water-ice table at depths less than a few decimeters at latitudes greater than 45° (Prettyman *et al.*, 2017). The GRaND data indicate that the top meter of the regolith contains only about 10 wt % water ice (assuming 20% porosity), when averaged over broad spatial scales. Water ice is expressed in small-scale regions on Ceres' surface, in association with impact craters and mass wasting. Within Oxo crater, km-scale patches of water ice are associated with slumping regions that may have recently exposed ice from the near subsurface (Combe *et al.*, 2019). Nine additional surface exposures of water ice (<7 km^2 total) have also been discovered at latitudes >30° and in similar geologic contexts: they occur in fresh impact craters and are often associated with mass wasting features (Combe *et al.*, 2019).

Since ice is not thermodynamically stable on Ceres' surface for appreciable geologic timescales, except in the polar regions (Hayne and Aharonson, 2015; Landis *et al.*, 2017), these ice patches must represent relatively recent exposures. Permanently shadowed craters at Ceres' poles that display higher albedos than surrounding areas are likely surficial deposits of water ice (Platz *et al.*, 2016; Schorghofer *et al.*, 2016; Ermakov *et al.*, 2017b).

Ceres' surface also shows a variety of morphologies that testify to abundant water ice in the uppermost ~10 km of the crust (Sizemore *et al.*, 2019). In particular, lobate flows analogous to water-ice flows on Earth, Mars, and possibly Titan, are also found on Ceres. These lobate flows are morphologically distinct from the predominantly dry mass-wasting processes observed on Vesta and are more numerous toward the cooler poles (Buczkowski *et al.*, 2016; Schmidt *et al.*, 2017; Scully *et al.*, 2018; Chilton *et al.*, 2019). Also, pitted terrains that share morphological characteristics with pitted terrain units on Mars and Vesta (Denevi *et al.*, 2012; Tornabene *et al.*, 2012) have been reported in seven impact craters on Ceres so far. The existence of these features has been interpreted as evidence that volatiles buried at shallow depths in Ceres' subsurface have undergone some degree of sublimation following impact-produced heating (Sizemore *et al.*, 2017, 2019).

3.2. Ceres' interior structure and evidence for an early global ocean

The degree-2 gravity field and inferred moment of inertia from Dawn observations indicate partial internal differentiation and relaxation to almost full hydrostatic equilibrium

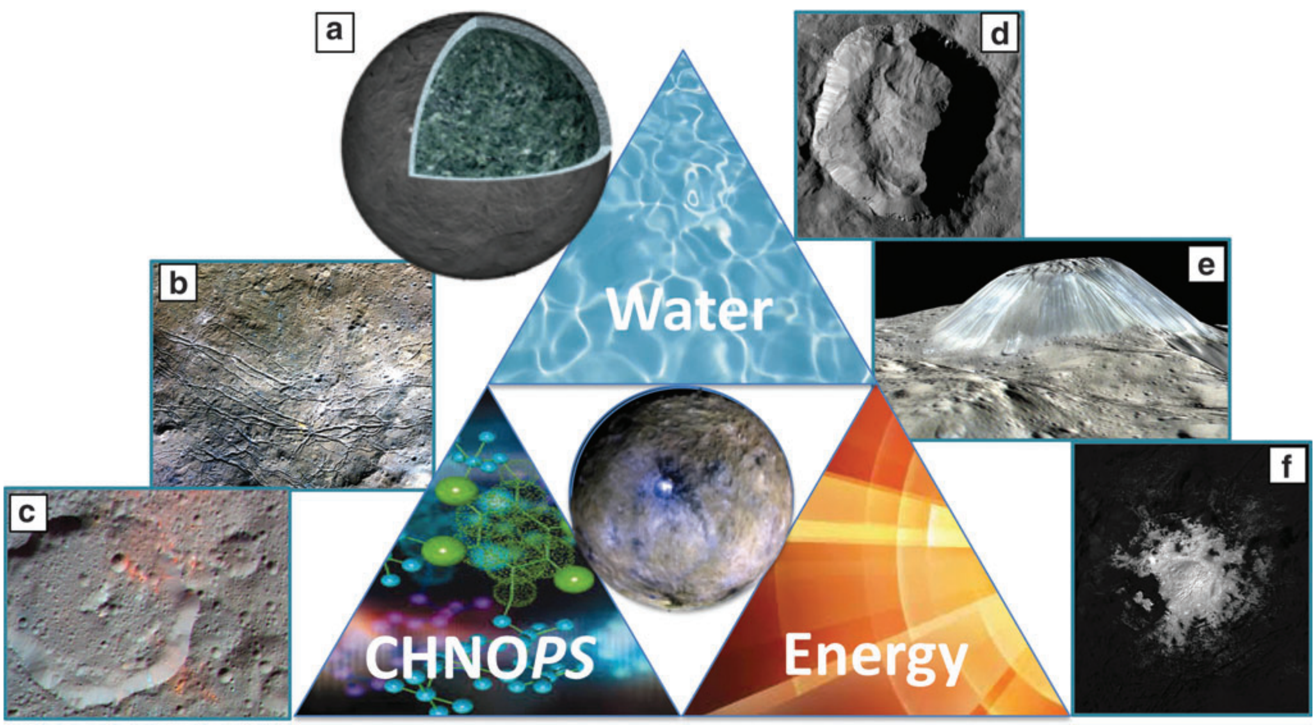

FIG. 1. Summary of Dawn's observations of Ceres addressed in the text. Credit for individual images: NASA/JPL/Caltech/IAPS/MPS/DLR/INAF/ASI. **(a)** Geophysical data confirmed the abundance of water ice and the need for gas and salt hydrates to explain the observed topography and crustal density. **(b)** Various types of carbonates and ammonium chloride have been found in many sites across Ceres' surface (*e.g.*, salts exposed on the floor of Dantu crater). **(c)** Ernuter crater (~52 km, above) and its area present carbon species in three forms (reduced in CxHy form, oxidized in the form of carbonates, and intermediate as graphitic compounds.). **(d)** Ceres shows extensive evidence for water ice in the form of ground ice and exposure via mass wasting and impacts (Left: Juling crater, ~20 km). **(e)** Recent expressions of volcanism point to the combined role of radiogenic heating and low-eutectic brines in preserving melt and driving activity (Left: Ahuna Mons, ~4.5 km tall, ~20 km diameter). **(f)** Impacts could create local chemical energy gradients in transient melt reservoirs throughout Ceres' history (Left: Cerealia Facula, ~14 km diameter).

(Park *et al.*, 2016). Admittance analysis indicates that Ceres is differentiated into a low-density crust (∼ 1200–1300 kg/m^3) and rocky mantle (2390–2450 kg/m^3) (Ermakov *et al.*, 2017a) (Fig. 2). The crustal thickness is about 40 km on average, but varies from ∼ 25 to 55 km (Ermakov *et al.*, 2017a). The low crustal density implies a silicate volume fraction of less than 20% (Ermakov *et al.*, 2017a). However, a crust dominated by water ice is inconsistent with observations of numerous impact craters, other morphological features on Ceres' surface, and ∼ 16 km of total topographic relief (Bland, 2013; Buczkowski *et al.*, 2016).

This suggests that the outer layer is stiffer than previously thought and contains ≤40% water ice and void space by volume (Bland *et al.*, 2016). Furthermore, the crust's high strength and low density have been interpreted as evidence for abundant salts and/or gas hydrates, hereafter referred to as ''clathrates,'' (Bland *et al.*, 2016; Fu *et al.*, 2017) starting a few kilometers below the surface (Sizemore *et al.*, 2019). This is consistent with the outcome of geochemical simulations of the freezing of an early ocean (Castillo-Rogez *et al.*, 2018).

Separation of a rocky mantle and ice-rich crust involves at least partial melting of Ceres' volatile phase on a global scale (McCord and Sotin, 2005). This event must have happened early in a body, whose sole internal heat source is radioisotope decay. Castillo-Rogez and McCord (2010) showed that long-lived radioisotopes alone cannot lead to the separation of a volatile-rich shell. They concluded that Ceres had to form early (a few My after the beginning of the solar system) to benefit from additional intense heat from the short-lived aluminum-26 radioisotope. Short-lived radioisotopes are recognized as being responsible for promoting early melting and aqueous alterations in the parent bodies of carbonaceous chondrites (*e.g.*, Keil, 2000). Another compelling line of evidence for global, pervasive aqueous alteration early in Ceres' history is its hydrated surface of remarkably homogeneous composition (Ammannito *et al.*, 2016) (see Section 3.3).

The low mantle density inferred by Ermakov *et al.* (2017a) indicates pervasive aqueous alteration. Fu *et al.* (2017) concluded that the low rocky mantle density indicates that temperatures remained low in the course of Ceres' history, less than the dehydration temperatures of phyllosilicates (>600°C). Beyond these findings, constraints are lacking on Ceres' internal evolution, particularly the period during which the dwarf planet hosted a global ocean. There are little data about this early period left in the present-day geomorphology. Thus, the range of possible ocean lifetimes is bounded by models: from a few hundred million years if the mantle was compact and lithified (*e.g.*, Castillo-Rogez and McCord, 2010) to several billion years, and possibly until present, if the interior maintained a convecting ''mudball'' (Travis *et al.*, 2018) or if insulating material in the crust impeded heat loss and helped preserve a liquid briny layer tens of km thick at the base of the crust (Castillo-Rogez *et al.*, 2019a; Quick *et al.*, 2019).

Overall, combined gravity and topography data indicate Ceres' density profile is akin to that of the icy moons of the outer Solar System, specifically the ocean-bearing Enceladus. Indeed, gravity data obtained at Enceladus with the Cassini mission also yielded a rocky mantle with a density of ∼ 2400 kg/m^3 (Iess *et al.*, 2014) and an ice-dominated shell.

3.3. *Composition and availability of major elements essential for biology*

Dawn observations have confirmed that Ceres' rocky material has been extensively processed by liquid water on a global scale (De Sanctis *et al.*, 2015; Ammannito *et al.*,

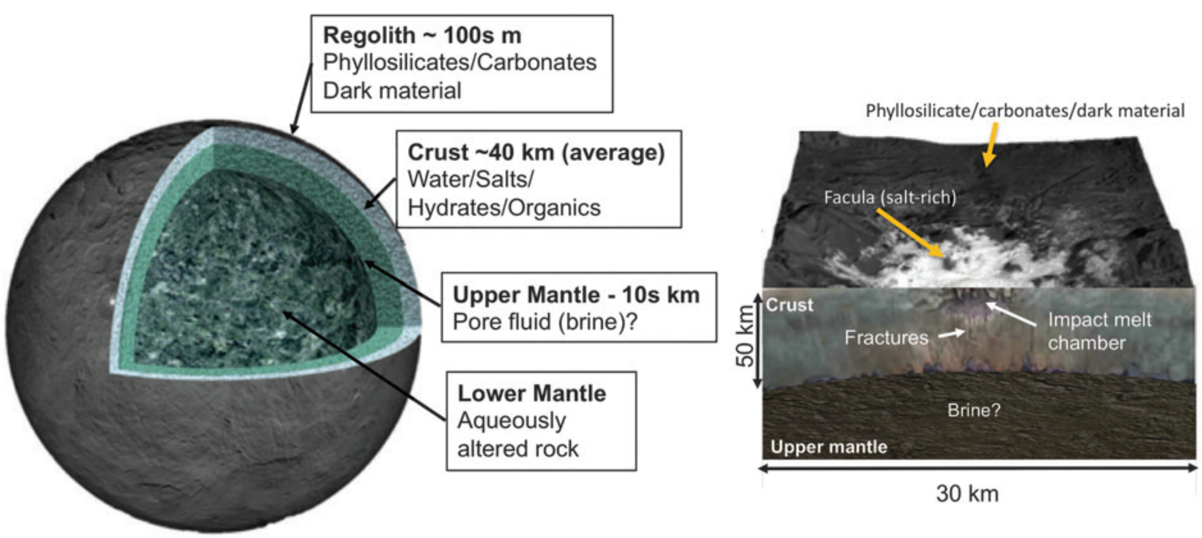

FIG. 2. Left: Global interior structure for Ceres: a ∼ 40-km thick (average) strong crust is composed of rock+ice+salts+clathrates with no more than ∼ 40% ice (Bland *et al.*, 2016; Ermakov *et al.*, 2017a; Fu *et al.*, 2017). It overlays a rocky mantle with a weak upper layer with brine-filled pore space that controls the global shape (Fu *et al.*, 2017). Right: Possible structure of the crust inferred below Occator Crater's faculae, in a region where the crust is ∼ 50 km thick (Ermakov *et al.*, 2017a). Impact craters could create transient melt chambers. Large impacts could also introduce or re-enact fractures allowing for the upwelling of deep brines. This rendition assumes that the impact melt reservoir was originally larger in extent but is mostly frozen at present, except for brines supplied from the deeper reservoir (Hesse and Castillo-Rogez, 2019). (Credit: NASA/JPL-Caltech/UCLA/MPS/DLR/IDA for the Occator image; crust rendition modified from Britney Schmidt/Dead Pixel FX/Univ. of Texas at Austin.).

2016; Prettyman *et al.*, 2017). Abundant mineral products of aqueous alteration are exposed on Ceres' surface, providing detailed insight into the chemistry of past and perhaps present liquid water environments. While this section follows this line of thought, one cannot rule out that Ceres' regolith could contain a significant fraction of infalls (Vernazza *et al.*, 2017; Marchi *et al.*, 2018). In the latter case, the information contained in the mineralogy of the low-albedo background material would only be marginally relevant to understanding Ceres' evolution, and only the bright material found at discrete sites would be the surface component that is truly representative of Ceres (Marchi *et al.*, 2018), with potentially some deviation due to additional, local, impact-produced hydrothermal alteration.

Ceres' near-infrared spectrum, as observed by VIR, is best fit by a mixture of ammonium-bearing phyllosilicates, magnesium-bearing phyllosilicates, carbonates, and a dark, spectrally featureless component whose nature is unknown (De Sanctis *et al.*, 2015). The surface mineralogy of Ceres can be reproduced qualitatively with geochemical models that include the interaction of liquid water containing carbon- and nitrogen-rich volatiles with silicates and organics of chondritic composition at temperatures below 50°C (Neveu *et al.*, 2017), consistent with conditions expected in Ceres' early ocean (*e.g.*, Travis *et al.*, 2018), and a water to rock ratio >2 (Castillo-Rogez *et al.*, 2018). Ceres' average surface spectral properties are similar as the Ivuna (CI) chemical group of carbonaceous chondrites (McSween *et al.*, 2018) and it also shows major differences to CI chondrites, such as the presence of ammoniated clays and salts, and a greater variety of carbonates. This includes sodium carbonates, which have not been found in CI chondrites.

As illustrated in Fig. 3, sodium carbonate is also found in Enceladus' plumes (Postberg *et al.*, 2011) and on Earth, where it is typical of alkaline aqueous environments (Zolotov, 2007; Marion *et al.*, 2012). Additional sites displaying sodium carbonate are found with their hydrated form (Carrozzo *et al.*, 2018) and exposed ice, mostly in association with impact craters and landslides (*e.g.*, in Oxo crater). This suggests that abundant material of aqueous origin is present at shallow depths. Many additional bright spots of unknown nature are also found on crater rims (Stein *et al.*, 2017).

As an outstanding example of ''bright spots,'' the Occator facula material (and potentially other faculae formed on crater floors) is thought to have originated in liquid brine reservoirs (De Sanctis *et al.*, 2016; Vu *et al.*, 2017; Quick *et al.*, 2019; Thomas *et al.*, 2019) or transient near-surface brines resulting from impact-induced heating (De Sanctis *et al.*, 2016; Zolotov, 2017; Bowling *et al.*, 2019; Hesse and Castillo-Rogez, 2019). The carbonate/ammonium/sodium composition of these brines is the same as the liquids that must have equilibrated with the minerals that blanket Ceres' surface (Neveu *et al.*, 2017; Castillo-Rogez *et al.*, 2018). Near the surface, these liquids subsequently underwent freezing and desiccation (Vu *et al.*, 2017; Castillo-Rogez *et al.*, 2018; Thomas *et al.*, 2019). The compositional gradient observed across the dome in the central facula in Occator (called Cerealia Facula) (Raponi *et al.*, 2019) indicates an evolution of the cryomagma source, consistent with modeling by Quick *et al.* (2019).

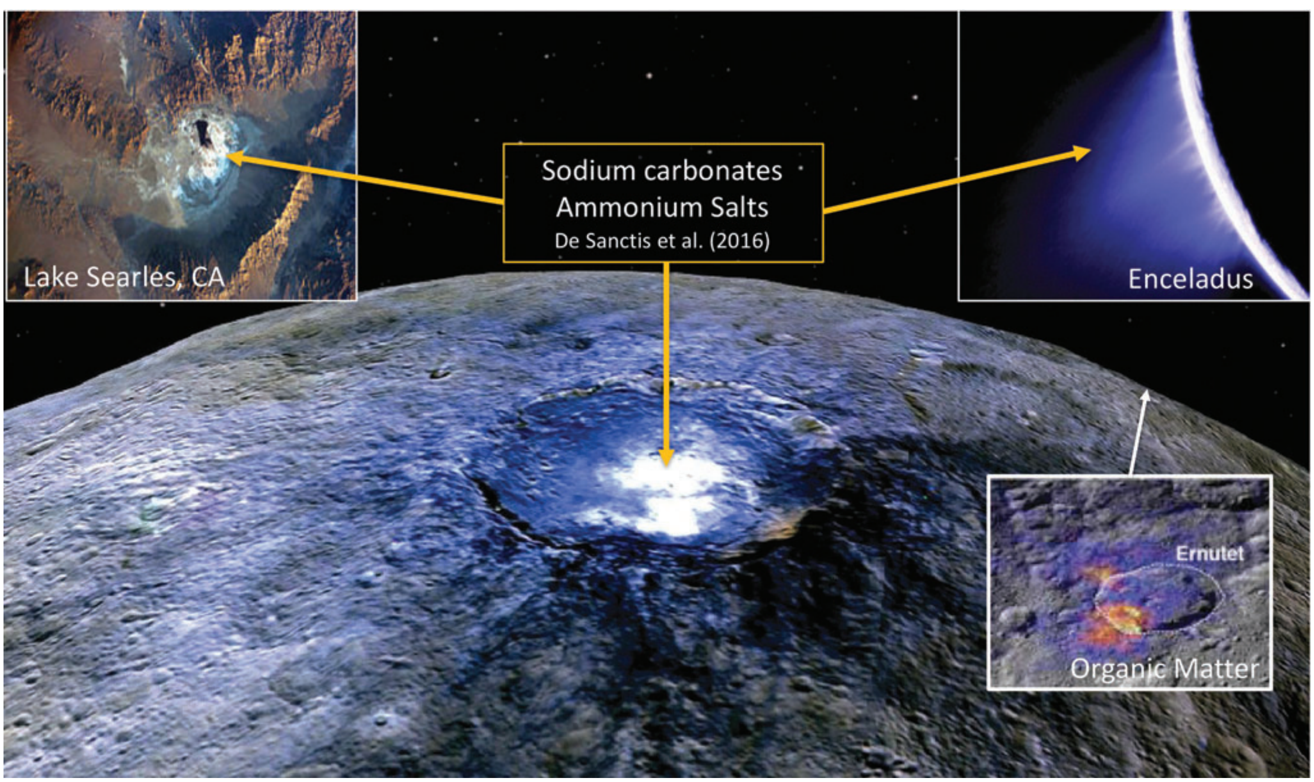

FIG. 3. Ceres' surface shows mineralogy found only on Earth and Enceladus, so far. More than 100 bright spots emerge from a globally homogeneous regolith. The most prominent are the faculae found in Occator crater, composed of sodium carbonate, a compound found so far only on Earth and in Enceladus' plumes.

Thus, reduced nitrogen is abundant enough to be detected globally from orbit both in the average dark surface and in the bright deposits. Among other bioessential elements, sulfur has proved elusive. It is predicted to exist on Ceres in the form of sulfides (Castillo-Rogez *et al.*, 2018), but these compounds do not have an obvious signature in the wavelength range of VIR. Sulfur-rich species have been suggested from ultraviolet observations with the *Hubble Space Telescope* (HST) (Hendrix *et al.*, 2016). Bu *et al.* (2019) also pointed out that sulfates could be present but not detectable because of the impact of space weathering on their spectral signature.

Carbon has been found in the form of carbonates and organic compounds. Carbon dioxide and/or methane are also believed to be present in the form of clathrates in the crust (Fu *et al.*, 2017; Castillo-Rogez *et al.*, 2018). Aliphatic organics have been reported at specific locations, in particular the Ernutet crater (De Sanctis *et al.*, 2017; Pieters *et al.*, 2018; Fig. 3). Their intimate association with material of aqueous origin suggests these compounds formed in Ceres' interior. Impact simulations suggest that the large fraction of organics found at Ernutet is not compatible with the high temperatures involved in exogenic delivery (Bowling *et al.*, 2020). Kaplan *et al.* (2018) found that the Ernutet organics cannot be fitted with typical organic matter from carbonaceous chondrites, unless abundances in excess of 45% are involved. Instead, De Sanctis *et al.* (2017, 2019) and Kaplan *et al.* (2018) suggest a better fit with terrestrial organics with a higher H/C ratio than the chondritic organics; kerogen was fit at a level of 5–15% on average, while terrestrial asphaltite was fit up to about 25% (De Sanctis *et al.*, 2019).

Other types of organic compounds not detectable by VIR are also likely to be present. GRaND data indicate the presence of C in the global bulk regolith, perhaps in concentrations greater than the $\sim$3.5 wt % found in the CI chondrites (Prettyman *et al.*, 2017). This study placed bounds on magnetite and troilite, leaving graphitized C, perhaps derived from the exposure of organics to ionizing radiation, as a plausible darkening agent. GRaND measurements of H and Fe can be fitted by carbonaceous materials, with C concentrations in excess of 10 wt % (Prettyman *et al.*, 2019a). The addition of mineral constraints from VIR suggests that C concentrations could be as high as 20 wt % if much of the surficial C is graphitized (Marchi *et al.*, 2018). Using HST observations, Hendrix *et al.* (2016) suggested that Ceres' dark component is graphitized carbon produced from the weathering of organics by charged particles.

Other elements of astrobiological importance that have low cosmochemical abundances (<1 wt %, *e.g.*, Lodders, 2003), such as phosphorus, could be detected from the orbit.

3.4. Geological evolution

Ceres' surface testifies to a rich geological history. It is not the purpose of this article to review the many aspects of Ceres' geological evolution (see, *e.g.*, Williams *et al.*, 2018). To briefly summarize, Ceres' surface is relatively old with two regional geological units: the high Hanami Planum that is >2 Gy old (Frigeri *et al.*, 2018), and the surrounding lowlands, which have been interpreted as basins (planitiae) created by large impacts (Marchi *et al.*, 2016). The latter suggests regional resurfacing accompanied with the removal of 100-km large craters (Marchi *et al.*, 2016). Most of the long-term evolution of Ceres has been driven by impacts with three types of consequences: (1) exposure of fresh material and local resurfacing with ejecta (*e.g.*, Palomba *et al.*, 2019); (2) gardening and mixing of the regolith with ice from the crust (Prettyman *et al.*, 2019b); and (3) in the case of large impacts, input of heat into the crust that could drive local, short-lived activity (Bowling *et al.*, 2019).

However, it was also suggested that the many domes (tholi, montes) found on Ceres' surface (Sizemore *et al.*, 2019) could be formed from episodes of cryovolcanic activity that lasted for several billion years up until the present (Sori *et al.*, 2018). The rest of this section focuses on available evidence for recent (<$\sim$100 My) geological activity.

The Dawn observations have revealed ample evidence for a geology driven, in part, by an abundance of volatiles and salts (*i.e.*, brines). The likely role of brines in driving cryovolcanism is indicated by features such as the Occator faculae as well as Ahuna Mons and more ancient features of potentially similar origin (Ruesch *et al.*, 2016; Sori *et al.*, 2017, 2018; Quick *et al.*, 2019). Buczkowski *et al.* (2016) identified additional cryovolcanic features on the dwarf planet.

Ahuna Mons is an $\sim$4-km-high and $\sim$21-km-wide mountain that is interpreted as a viscous cryovolcanic dome formed by the ascent of cryomagma from the depth and subsequent eruption onto the surface in a manner akin to lava dome emplacement on Venus and Europa (Quick *et al.*, 2014, 2016, 2017). This cryomagma is thought to consist of low-eutectic salt melt, ice, and silicate solid (Ruesch *et al.*, 2016). Abundant sodium carbonate is found on the flanks of the mountain (Zambon *et al.*, 2017; Carrozzo *et al.*, 2018). Sori *et al.* (2018) interpreted multiple tholi as the expression of similar domes that have viscously relaxed; however, Ahuna Mons' unique large gravity anomaly suggests a low ice content (Ruesch *et al.*, 2019a). Based on gravity data analysis, Ruesch *et al.* (2019a) connect the formation of Ahuna Mons to upwelling of a dense slurry from the mantle.

Other geological evidence for recent activity (<2 My) (Nathues *et al.*, 2019) is expressed at the crater Occator, as shown in Fig. 4. The bright spots, or faculae observed in the 92-km-diameter crater, mainly consist of sodium carbonates, which may represent the residue of crystallized brines extruded onto the crater floor from depth (De Sanctis *et al.*, 2016; Quick *et al.*, 2019). The crater is dated at $\sim$22 My and the internal lobate deposits are contemporaneous within the error of the model ages, when using the lunar-derived chronology model (Neesemann *et al.*, 2019). Facula ages are more difficult to constrain because of their small area. Their brightness suggests a recent emplacement since micrometeorites tend to darken surface material on timescales of a few My (see Stein *et al.*, 2017; Thangjam *et al.*, 2018). Quick *et al.* (2019) and Ruesch *et al.* (2019b) introduced models where at least some of the faculae are created by the venting of brines from a deep reservoir.

In the Quick *et al.* (2019) model, the Occator faculae were created when brines originating from a cryomagma chamber beneath Occator's floor erupted onto Ceres' surface. Upon being emplaced in Ceres' zero-pressure surface environment, these brines would have subsequently boiled, launching vapor, ice, and salt particles on ballistic trajectories. The buildup of these salts could have formed the faculae. It is also possible that the faculae were formed when fractures containing salty liquids and <2 wt % of a

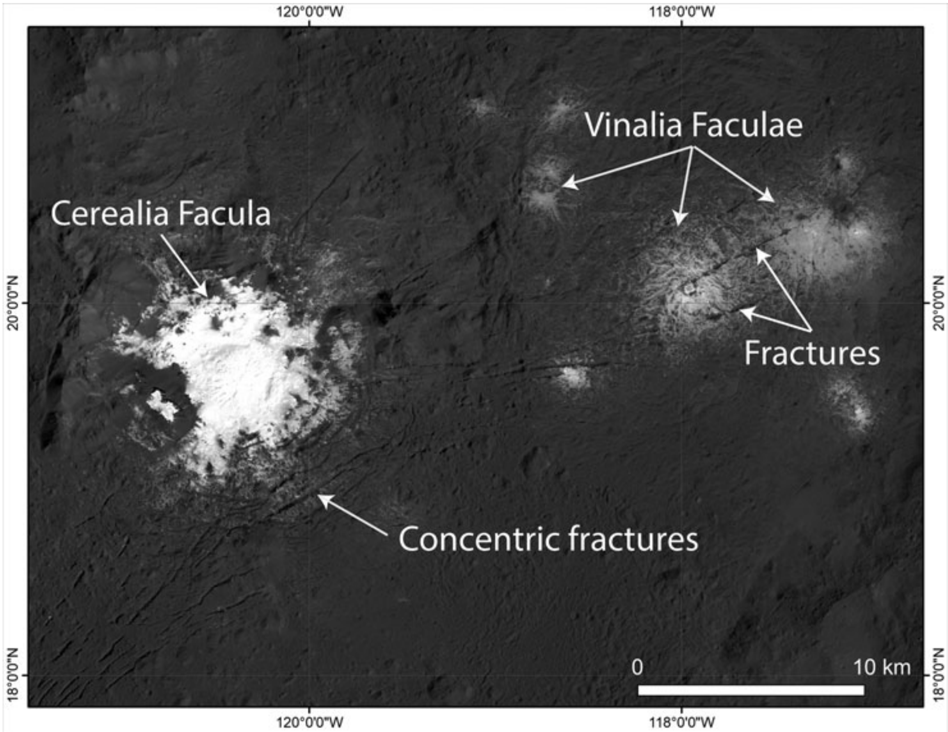

FIG. 4. Geological context for the faculae found inside Occator crater. The brightness stretch is chosen to emphasize the network of fractures associated with the various faculae. The concentric fractures around the Cerealia Facula (left) are interpreted to form during the collapse of the central pit within which the Cerealia Facula is located (Buczkowski *et al.*, 2019b). The Vinalia Faculae are created by vents associated with fractures (Ruesch *et al.*, 2019). Credit: NASA/JPL/Caltech/IAPS/MPS/DLR.

volatile constituent such as water vapor, CH_4, CO_2, or NH_3 intersected with Ceres' surface. Upon reaching the surface, volatiles in solution would have exsolved, causing eruptive boiling and resulting in salt particles being launched on ballistic trajectories that were wide enough to create the faculae (Quick *et al.*, 2019). Similarly, Ruesch *et al.* (2019b) found that ''brine fountaining'' was the most plausible explanation for the formation of the faculae. During this process, briny liquid extruded onto the surface, followed by flash freezing of carbonate and ice particles, particle fallback, and finally, sublimation of any residual ice.

Diurnal variations of Occator's Cerealia Facula (the central bright deposit) were initially interpreted as a signature of haze (*i.e.*, water vapor lifting small particles) (Thangjam *et al.*, 2016); however, no evidence has been found in data from the VIR instrument for the presence of water ice within Occator (De Sanctis *et al.*, 2016). The nature of these brightness variations is currently being studied.

4. Ceres' Astrobiological Potential Over Time and at Present

We assess the implications of observational results from the Dawn mission for Ceres' astrobiological significance: the prospect for the preservation of liquid until present (Section 4.1); possible active and passive mechanisms driving internal activity (Section 4.2); constraints on Ceres' early ocean composition (Section 4.3) and the prospect for the maintenance of chemical gradients until present (Section 4.4); and possible origins for the organics found on Ceres' surface as well as the prospect for life to arise on Ceres (Section 4.5). This information is used to assess the place of Ceres in the ROW and justify why it was identified as a ''*candidate*'' ocean world* (Hendrix *et al.*, 2019). The current state of knowledge of Ceres in the ROW framework is summarized in Table 1.

4.1. Existence and nature of liquid in Ceres at present

There are two lines of evidence for the existence of liquid in Ceres at present. First, the global relaxation of topographical features ≥250 km was interpreted by Fu *et al.* (2017) as evidence for the presence of a weak layer below the crust, that is, in the upper mantle. From the viscosity constraint $<10^{21}$ Pa s, Fu *et al.* inferred that the weak layer should contain a small fraction of pore fluids in a matrix of phyllosilicates. Modeling cannot provide a more specific range about the thickness or viscosity of that inferred weak layer except that it extends at least 60 km into the mantle (Fu *et al.*, 2017) (Fig. 2). Hence, these geophysical models are currently not efficient to distinguish between the interior models of Travis *et al.* (2018; ''mudball'' mantle†) and Castillo-Rogez and McCord (2010; more compact mantle).

*The Roadmap for Ocean Worlds targets bodies that currently hold deep oceans or surface liquid in the case of Titan.

†In the ''mudball'' model, Ceres' mantle is a mixture of silicate particles (phyllosilicate fines but not strictly limited to a particular size range) in a suspension in brine.

Table 1. Assessment of the Current State of Knowledge of Ceres with Respect to the Questions Defined in the Roadmap for Ocean Worlds (Hendrix *et al.*, 2019)

Question	*Assessment*	*References*
Goal I. Identify ocean worlds in the solar system.		
I.A. Is there a sufficient energy source to support a persistent ocean?		
A.1 Is there remnant radiogenic heating?	Yes, combined with low-thermal conductivity materials.	McCord and Sotin (2005) Castillo-Rogez and McCord (2010) Neveu *et al.* (2015) Neveu and Desch (2015) Neumann *et al.* (2015) Travis *et al.* (2018) Castillo-Rogez *et al.* (2019a)
A.2 Is there gravitational energy from a parent planet or satellite?	No. Negligible forcing from solar tides.	N/A
A.3 Can the planet or satellite convert available tidal energy into heat?	N/A	N/A
A.4 Are the planet or satellite's orbital or rotational properties favorable to tidal dissipation?	N/A	N/A
I.B. Are signatures of ongoing geologic activity (or current liquids) detected?		
B.1 Do signatures of geologic activity indicate the possible presence of a subsurface ocean? (surface hotspots, plumes, crater-free areas, volcanoes, tectonics)	• Crater-free bright deposits, including Vinalia faculae ascribed to fountaining deposits and Cerealia dome. • Ahuna Mons likely a young cryovolcano, possibly many more in the past. • Fractured-floor craters consistent with underlying cryomagmatic intrusions.	Ruesch *et al.* (2016, 2019a) Buczkowski *et al.* (2016) Sori *et al.* (2017, 2018) Fu *et al.* (2017) This study, Section 3.4
B.2 Does the body exhibit tidal and/or rotational evidence indicating the presence of a subsurface ocean?	The absence of any significant forcing potential implies the dynamical signature of a subsurface ocean would be absent or too weak to be detectable.	Rambaux *et al.* (2011)
B.3 Does the gravity and topography of the body indicate the presence of a subsurface ocean?	Gravity and topography indicate weakening of the crust at ~ 100 km depth, which could be explained by a subsurface ocean.	Fu *et al.* (2017) Ermakov *et al.* (2017a) This study, Section 3.2
B.4 Are there temporal changes observed at the body that would indicate the presence of a subsurface ocean?	Not at the resolution of the Dawn observations. Potential time-varying haze associated instead with surface ice sublimation. Energetic particle bursts associated with exosphere.	A'Hearn and Feldman (1992) Küppers *et al.* (2014) Russell *et al.* (2016) Nathues *et al.* (2015) Thangjam *et al.* (2016)
B.5 Is there an atmosphere or exosphere that could be linked with the presence of a subsurface ocean?	Ceres has an exosphere whose origin may be in surface ice patches.	Russell *et al.* (2016) Landis *et al.* (2017)
B.6 Does the electromagnetic response of the body indicate the presence of a subsurface ocean?	Could not be measured with Dawn. Energetic particle bursts associated instead with exosphere.	Russell *et al.* (2016)
B.7 Can the surface composition be linked with the presence of a subsurface ocean?	There is one occurrence of material exposed on the surface (Ahuna Mons) that points to an origin in a liquid layer, brine pocket, or fluid-filled porous/fractured layer.	This study, Section 3.4
B.8 Is the signature of a surface liquid observed (*e.g.*, specular reflection)?	No, surface liquid is not stable since Ceres has no atmosphere.	N/A

(*continued*)

Table 1. (Continued)

Question	*Assessment*	*References*
I.C. How do materials behave under conditions relevant to any particular target body?		
C.1 What are the phase relations of material composing ocean worlds at relevant pressures and temperatures?	Understood in the case of brines and clathrate hydrates but not fully in the case of mixtures, hydrous salts, and phyllosilicates.	Prieto-Ballesteros and Kargel (2005) Kargel (1991)
C.2 What is the composition and chemical behavior of materials composing ocean worlds?	Ceres' bulk composition observed to comprise silicates (largely hydrated), water ice, salts (carbonates, chlorides), organic carbon, Fe. Indirect evidence for clathrate hydrates and other materials present in carbonaceous chondrites. These materials are largely at chemical equilibrium, but still subject to modifications from transport processes (*e.g.*, cryovolcanism) and radiolysis.	De Sanctis *et al.* (2015, 2016) Prettyman *et al.* (2017) Ermakov *et al.* (2017a) Fu *et al.* (2017) Neveu *et al.* (2017) Castillo-Rogez *et al.* (2018) Marchi *et al.* (2018)
C.3 What are the rheological mechanisms by which material deforms under conditions relevant to ocean worlds?	Understood for end-member materials (silicates, water ice, clathrate hydrates, salts), less so for mixtures.	For example, Durham *et al.* (2003, 2005)
C.4 How does energy attenuation/dissipation occur under conditions relevant to ocean worlds?	Negligible tidal dissipation (of solar tides) inside Ceres.	N/A
C.5 What are the thermophysical properties of material under conditions relevant to ocean worlds?	Understood for end-member materials (silicates, water ice, clathrate hydrates, salts), less so for mixtures.	Clauser and Huenges (1995) Sirono and Yamamoto (1997) Waite *et al.* (2017) Castillo-Rogez (2011) Castillo-Rogez *et al.* (2019a) and references therein
Goal II. Characterize the ocean of each ocean world		
II.A. Characterize the physical properties of the ocean and outer ice shell		
A.1 What is the thickness, composition, and porosity of the ice shell (crust) and how do these properties vary spatially and/or temporally?	Thickness of porous/fractured outer crust is $\approx 40\,km$ with estimated $\approx 10\%$ porosity. Crust composed of silicates, <30–40% ice, salts, and likely clathrate hydrates. Viscosity decreases with depth from 10^{25} to $<10^{21}$ Pa s. Crustal strength can vary significantly at $\sim 100\,km$ scales.	Bland *et al.* (2016) Ermakov *et al.* (2017a) Fu *et al.* (2017)
A.2 What are the thickness, salinity, density, and composition of the ocean? How do these properties vary spatially and/or temporally?	Weak layer compatible with fluid reservoirs today is at average depth >40 km. Reservoir sizes are unknown. Salinity is presumably high, for example, saturation for NaCl brine at eutectic temperature is 23 wt % NaCl. Composition compatible with bright spot compositions and forward modeling of chondritic alteration estimated to comprise oxidized C, reduced N, Cl, and Na with possible Ca/Mg/K. As cooling/freezing progresses, lower eutectic Cl brines should dominate over carbonate brines.	Neveu and Desch (2015) Neveu *et al.* (2017) Castillo-Rogez *et al.* (2018) Travis *et al.* (2018) Quick *et al.* (2019)
A.3 What are the drivers for, and pattern of, fluid motion within the ocean?	Unknown. A past ocean may have been subject to geostrophic flow due to Ceres' fast spin ($\sim$9-h spin period today) and convective flow driven by thermal and/or compositional gradients, especially for a thick ocean. In remnant reservoirs, drivers may be compression due to the freezing of the remnant liquid and gas exsolution or clathrate decomposition.	Neveu and Desch (2015) Quick *et al.* (2019)

(*continued*)

Table 1. (Continued)

Question	*Assessment*	*References*
II.B. Characterize the ocean interfaces		
B.1. Characterize the seafloor, including the high-pressure ocean—silicate interaction	Ceres' incomplete differentiation makes it difficult to identify a seafloor interface. No such interface was detected with Dawn data. Even central pressures on Ceres are $\sim$300 MPa, three times higher than deepest seafloor on Earth. It has been suggested that former seafloor is present-day surface, if frozen ocean removed by impacts and sublimation.	Park *et al.* (2016) Castillo-Rogez *et al.* (LPSC 2016) Fu *et al.* (2017)
B.2. Characterize the ice/ocean interface	The interface between the icy crust and a past global ocean or present-day liquid reservoirs remains unconstrained by Dawn data. Surface topography and gravity measurements only indicate a decrease in crustal viscosity with depth.	Fu *et al.* (2017)
Goal III. Characterize the habitability of each ocean world		
III.A. What is the availability (type and magnitude/flux) of energy sources suitable for life, how does it vary throughout the ocean and time, and what processes control that distribution?		
A.1 What environments possess redox disequilibria, in what forms, in what magnitude, how rapidly dissipated by abiotic reactions, and how rapidly replenished by local processes?	Past redox disequilibria between oxidized ices/fluids and reduced rock have decreased to possibly zero by water/rock reactions. Locally and temporarily, disequilibria may be reestablished by comparatively rapid material movement during impact or volcanic events. Globally, disequilibria equivalent to a few percent, those at prealteration, are maintained by splitting of H_2O from radioactivity and exogenic surface irradiation.	Neveu *et al.* (2017) Bouquet *et al.* (2017) Castillo-Rogez *et al.* (2018) Strazzulla *et al.* (2005) This study, Section 4.4
A.2 (Where) is electromagnetic or other energetic radiation available? In what wavelengths or energy and intensity?	Energetic radiation from the Sun, galactic cosmic rays, and decay of radionuclides. Energy spectrum has not been measured.	Madey *et al.* (2002) Bouquet *et al.* (2017)
III.B. What is the availability (chemical form and abundance) of the biogenic elements, how does it vary throughout the ocean and time, and what processes control that distribution?		
B.1 What is the inventory of organic compounds, what are their sources and sinks, and what is their stability with respect to the local environment?	Aliphatic organic compounds detected in several places; endogenic origin confirmed; but an inventory is missing.	De Sanctis *et al.* (2017) Pieters *et al.* (2018) Kaplan *et al.* (2018)
B.2 What is the abundance and chemical form of nitrogen, oxygen, phosphorus, sulfur, and inorganic carbon, what are their sources and sinks, and are there processes of irreversible loss or sequestration relative to the liquid environment?	Nitrogen in the form of ammonium and suspected to be in the form of ammonia in remnant liquid layer; $\approx$20% carbon in regolith as carbonates and local organic compounds; surface suggested to be dark due to amorphous C; suggested elemental sulfur and/or SO_2 from observations in the ultraviolet; sulfides predicted by geochemical models (not detectable by Dawn's payload).	De Sanctis *et al.* (2015, 2016) De Sanctis *et al.* (2017) Prettyman *et al.* (2017) Hendrix *et al.* (2016) Neveu *et al.* (2017) Castillo-Rogez *et al.* (2018) This study, Section 3.3.

(*continued*)

Table 1. (Continued)

Question	*Assessment*	*References*
Goal IV. Understand how life might exist at each ocean world and search for life		
IV.A. What are the potential biomarkers in each habitable niche?		
A.1 What can we learn about life on ocean worlds from studying life on Earth?	Best analogues for any remaining Ceres habitats might be dark, cold, hypersaline environments with chemical disequilibrium driven by radiolysis. To our knowledge, no single environment combining all properties has been investigated on Earth. Some terrestrial environments do combine part of these properties (*e.g.*, solutes found at the triple junctions of glacier ice).	Bowman *et al.* (2000) Lin *et al.* (2005) Blair *et al.* (2007) Yau *et al.* (2013) Christner *et al.* (2014)
A.2 What niches for life are possible on ocean worlds?	Porosity in the mantle and in remaining endogenic or impact-produced melt reservoirs.	Neveu *et al.* (2015) Travis *et al.* (2018)
A.3 What can we learn about life by understanding the history of ocean worlds from their formation to the present?	As a no-tidal-heating end-member of ocean worlds, Ceres enables the study of habitat persistence in energy-limited worlds.	Hendrix *et al.*, (2019)
A.4 What should be our target indicators? (Life Detection Ladder)	Features more likely to have been preserved above abiotic backgrounds: patterns and structural preferences in organic compounds; elemental distributions; isotopic fractionations; cell-like morphologies.	Neveu *et al.* (2018) This study, Section 4.5.3
A.5 How do we distinguish extant from extinct life in environments in which life might develop, and which timescales (*e.g.*, for metabolism, reproduction, dormancy) matter?	N/A	N/A
IV.B. How to search for and analyze data in different environments?		
B.1 How can we look for life on an ocean world remotely (from orbit or during a flyby)?	Orbital measurement techniques are not suited for determining biomolecules. Dawn found evidence of organic matter but could not accurately characterize the nature of that material. Other life signatures that are expected on planets (*e.g.*, vegetation, oxidants, and reductants in atmosphere) are not applicable here.	
B.2 How can we look for life on an ocean world *in situ* (landed, underwater, plume) investigations?	Targeting high-resolution mapping can help better understand the geological context, including the provenance of the bright spots, organics, and ammonium-bearing material. This is essential to establish the abiotic background against which any biological signatures of A.4 can be sought with an appropriate payload (*e.g.*, Europa Lander Report; Hand *et al.*, 2017).	
B.3 How can we look for life on an ocean world with sample return science?	For a Ceres sample return, target indicators of A.4, but more complex measurements could be carried out such as organic compound-specific isotopic analyses to ascertain their biological vs. abiotic origin (*e.g.*, Badin *et al.*, 2016; Close, 2019).	
B.4 Which science operational strategies should be used to detect life on ocean worlds?	At Ceres, landing first, looking for A.4 indicators, and performing a sample return if several of these indicators are found. Promising landing sites would be those showing evidence for recent delivery of material from the subsurface (Occator faculae) to minimize abiotic destruction of any indicators given in A.4 by space weathering, as well as those showing evidence for out-of-equilibrium bioessential compounds (Ernutet).	

N/A, Not applicable.

Second, the recent extrusion of brines at the Occator Crater and the formation of Ahuna Mons <150 My ago both require feeding from a deep brine reservoir (Quick *et al.*, 2019; Ruesch *et al.*, 2019a, 2019b; Scully *et al.*, 2019; Raymond *et al.*, 2020) (Fig. 2). The possibility for a small amount of brine in Ceres at present, at least on a regional scale, is viable from a geophysical standpoint for a 40-km-thick average crust that includes at least 40 vol.% hydrates (gas and salt) (Castillo-Rogez *et al.*, 2019a). Clathrates have the same density as ice but their thermal conductivity is at least one order of magnitude less and their viscosity at least three orders of magnitude greater than ice at the same temperature. Hence, they are the most likely compound responsible for Ceres' low-density and high-strength crust (Section 3.2). Porosity can also contribute to decreasing thermal conductivity but tends to weaken the crust and is thus expected to be limited in extent and likely in the form of macroporosity (*i.e.*, local), as indicated by the high number of polygonal craters (Otto *et al.*, 2016).

While the porous medium suggested by Fu *et al.* (2017) does not meet the general definition of ''ocean'' as a vast layer of water, it could be a medium analogous (at least physically) to the pelagic environment of Earth's deep ocean in terms of pressure, but at colder temperatures. The temperature of that layer may be subzero, set by the eutectic temperature of remnant brines (Castillo-Rogez *et al.*, 2019a) or much warmer owing to slow heat loss (Travis *et al.*, 2018). The mantle porosity governs the extent of the interface at which liquid water and rock can interact, that is, where chemical gradients can arise and bioessential species may become concentrated. Porosity could also have developed due to fracturing of a cohesive mantle during evolution. Neveu *et al.* (2015) showed that thermal stresses due to cooling could lead to pervasive cracking down to the center of Ceres.

4.2. Recent active vs. passive geological activity

Evidence for recent geological activity has been most recently interpreted as resulting from three possible interior settings. In the setting described by Travis *et al.* (2018), thermal convection in a long-lived ocean triggers convective upwelling in the crust, which would be responsible for the observed domes. On Europa, the existence, spacing, and morphology of pits, spots, and domes have long been used to infer locations of enhanced local heating and the possibility of local liquid pockets in the ice shell (*e.g.*, Pappalardo *et al.*, 1998; Michaut and Manga, 2014). Recent work has also suggested that some of Europa's domes may have formed from eruptions of briny cryolava in areas of enhanced local heating (Quick *et al.*, 2017).

Diapirism offers another possible mechanism for material extrusion. The resemblance of Occator to lunar floor-fractured craters and the fractured surfaces of the Cerealia Dome might suggest formation by ascending diapirs (Buczkowski *et al.*, 2018a, 2018b; 2019). Ruesch *et al.* (2019b) considered several possible formation mechanisms for the faculae and concluded that brine extrusion from a vertical conduit, followed by flash freezing of ice, ejection of bright particles, and subsequent sublimation of any extruded liquids, was the most likely formation mechanism. Further modeling of the migration of briny fluids in vertical conduits, and the subsequent eruption of these fluids at Ceres' surface by Quick *et al.* (2019), confirmed that these processes were able to produce Occator's faculae. The emplacement of the large Ahuna Mons also seems to be best explained by the diapirism of a slurry of brine and silicate particles that Ruesch *et al.* (2019a) connect to the top of the mantle.

According to Ruiz *et al.* (2007), diapirs themselves could create transient habitable zones and/or reactivate dormant ones by warming the surrounding ice for hundreds of thousands of years. The same could be said for sills and fractures containing briny cryomagmas. However, more detailed investigation is needed to assess whether brine pockets could offer a propitious environment for halophiles (based on temperature and water activity, both of which are poorly constrained.) Neveu and Desch (2015) suggested that compressive stresses in a freezing brine reservoir could drive the upwelling of liquid/soft material in recent history. Recently, Quick *et al.* (2019) modeled this process and found it to be a viable means of transporting briny liquids to Occator's central region.

Finally, impact-produced heating could be responsible for producing local melt pool, as suggested below Occator's floor (Bowling *et al.*, 2019). Hesse and Castillo-Rogez (2019) suggested that reservoir could last up to ~ 10 My. Other large craters also display carbonates and other salts associated with fractures (*e.g.*, Dantu crater; Stephan *et al.*, 2018), suggesting that impact-produced melt was a common process on Ceres. Impact heating could also warm up the crust and drive solid-state convection arising from differential loading following impacts into a heterogeneous, icy crust (Bland *et al.*, 2019).

In summary, even if Ceres' heat production from radioisotope decay at $\sim 2\,\mathrm{mW/m^2}$ is low, hydrates and low-eutectic compounds could help maintain brines that drive geological activity until present. Brine mobility could serve as an important exchange process on Ceres, promoting the transfer of volatiles and organics between the subsurface and surface, potentially throughout Ceres' history if helped by large impacts and/or via diapirism (Ruesch *et al.*, 2019a). Impact mixing is another mechanism that could promote recycling of material in the first kilometers of Ceres' crust.

4.3. Evolution of ocean chemical and physical conditions until present

As noted above, the observed mineralogy implies that Ceres' material went through a phase of advanced aqueous alteration (De Sanctis *et al.*, 2015). Conditions in Ceres' ocean that led to the currently observed mineralogy are addressed at length by Neveu *et al.* (2017) and Castillo-Rogez *et al.* (2018). These studies suggest that the aqueously altered material on Ceres' surface reached chemical equilibrium as a result of advanced alteration. Modeling by Vance *et al.* (2016) also suggests that majority of Ceres' rock could be serpentinized; in comparison, bigger icy bodies with a lower water to rock ratio (*e.g.*, Europa) could preserve a fraction of their original bulk of anhydrous material over much longer timescales. Advanced aqueous alteration is also supported by the large occurrence of carbonates on Ceres in comparison with the Ivuna (CI) and Mighei (CM) chemical group of carbonaceous chondrites

(McSween *et al.*, 2018). This is reinforced by the presence of Mg-OH species rather than Fe-OH phyllosilicates on Ceres' surface (*e.g.*, Ammannito *et al.*, 2016).

The mixture of ammoniated clays, serpentine, and Mg/Ca carbonate is best explained by alteration in the presence of abundant water (water to rock ratio ≥2), a pH around 9–11, and a partial pressure of hydrogen log (P_{H2}) > −6 (Castillo-Rogez *et al.*, 2018). Experimental data indicate that the exchange of ammonium with cations (*e.g.*, K^+ and perhaps others such as Ca^{2+} and Na^+) may be promoted at temperatures <50°C [see Neveu *et al.* (2017) for a review of the literature]. Those mild temperatures appear consistent with the recent hydrothermal evolution modeling of Ceres (Neveu and Desch, 2015; Travis *et al.*, 2018). The high redox level and alkaline conditions are consistent with inferences at other large ice-rich bodies such as Europa (McKinnon and Zolensky, 2003; Zolotov and Shock, 2003) and Enceladus (Zolotov, 2007; Glein *et al.*, 2015).

The comparison with Enceladus may be particularly informative of Ceres' past (and perhaps present) habitability. Enceladus' liquids are also expected to be dominated by Na-Cl-CO_3 chemistry (Glein *et al.*, 2015). At Enceladus, the bulk water to rock ratio is likely above 0.6, assuming a 10-km-thick global ocean above a 195 km rocky mantle with 25% water-filled porosity consistent with observations (Choblet *et al.*, 2017; Neveu and Rhoden, 2019). This water to rock ratio is likely higher and closer to Ceres' water to rock ratio of ≥2 because Enceladus' ocean is thicker near the south pole (Iess *et al.*, 2014; Thomas *et al.*, 2016) and the mantle rock has not yet fully reacted with water (Waite *et al.*, 2017).

The pH of Enceladus' ocean is also alkaline, having been variously constrained to 8.5–10.5 (Sekine *et al.*, 2015), 11–12 (Glein *et al.*, 2015), and most recently 9–11 (Waite *et al.*, 2017; Glein *et al.*, 2018), similar to the conditions of aqueous alteration at Ceres. Ceres' mineral assemblages indicate formation $P_{H2} > 10^{-6}$ (Castillo-Rogez *et al.*, 2018), suggesting potential overlap in redox conditions with Enceladus. Direct H_2 mixing ratio measurements in Enceladus' plume indicate $P_{H2} \sim 10^{-2}$ (Waite *et al.*, 2017). Inside both worlds, the rocky interiors of density $\approx 2400\,kg/m^3$ (McKinnon, 2015; Beuthe *et al.*, 2016; Ermakov *et al.,* 2017a) seem to be hydrated and not fully differentiated from lower density ices. Based on radial density profiles, pressures of water/rock interaction are 9–60 MPa in Enceladus' mantle, compared with 17–300 MPa on Ceres.

Among key physicochemical conditions, only the temperature of interaction may be significantly higher for Enceladus, ≥90°C (Hsu *et al.*, 2015) and possibly up to 150–200°C (Sekine *et al.*, 2015), compared with ≤50°C on Ceres (Castillo-Rogez *et al.*, 2018). Lower temperature zones likely exist on Enceladus where hot fluids of interaction mix with colder seawater, which is near freezing at the base of Enceladus' ice shell. Therefore, being of similar size and composition, and with related physicochemical conditions, Ceres could share similarities with Enceladus in its habitability and astrobiological potential, at least for part of its history.

In the conditions inferred for Ceres' early ocean, iron is predicted to be in the form of green rust and sulfide, both dosed with nickel (Russell *et al.*, 2014; Tosca *et al.*, 2016; Halevy *et al.*, 2017; Branscomb and Russell, 2018). The counterpart residual liquid would be enriched in, among other things, chlorides, ammonium, and carbonate and bicarbonate ions. Metals would be scarce. Modeling of the freezing of Ceres' ocean (Zolotov, 2017; Castillo-Rogez *et al.*, 2018) reproduces the sodium bicarbonate and ammonium salts and carbonates found at Occator crater and other sites (De Sanctis *et al.*, 2016; Carrozzo *et al.*, 2018), which is consistent with experimental work (Vu *et al.*, 2017; Thomas *et al.*, 2019).

Progressive freezing of Ceres' ocean would increase its salinity. The residual liquid would become enriched in ammonia and chlorides (NaCl and KCl) with a pH equal to 7.5 (Castillo-Rogez *et al.*, 2018) and a eutectic temperature of 210 K. Thermal modeling shows that Ceres could preserve warmer temperatures at the base of the crust, >255 K until present day (Neveu *et al.*, 2015; Travis *et al.*, 2018; Castillo-Rogez *et al.*, 2019a).

4.4. Prospect for Ceres to preserve redox gradients until present

The qualitative match between Ceres' homogeneous surface and facula compositions to aqueously altered chondritic material and the corresponding altering fluids, respectively, suggests that Ceres reached global chemical equilibrium. However, several processes could contribute to local disequilibrium. The first process is the creation of a melt reservoir. The creation of this reservoir, as a result of impact heating, could foster serpentinization of anhydrous, exogenic material embedded in the regolith (see Marchi *et al.*, 2018). Any anhydrous, exogenic material embedded in the regolith (see Marchi *et al.*, 2018) would then be subject to aqueous alteration. Similarly, impactor material would represent a major component of any impact-produced melt reservoir (Bowling *et al.*, 2019). However, such events would be short lived, a few My at most (Fyfe, 1974).

A second mechanism is the possible creation or upsurge of liquid from the deep interior via fractures. This upwelled liquid may react with surface material, brought in by large impacts. The third mechanism is endogenic radiolysis: the radioactive decay of long-lived radioisotopes in the mantle can produce local redox gradients by affecting pore water (provided there is some porosity, due to fractures or incomplete compaction upon silicate sedimentation). In the rest of this section, we examine this last process more closely as it is a quantifiable, steady source of redox gradients.

This endogenic radiolysis of water can form multiple products (Le Caer, 2011) that can act as electron acceptors, including H_2O_2, and OH, as well as H_2, which can be an electron donor. The radiation powering this process would originate mainly from isotopes of potassium, thorium, and uranium (^{40}K, ^{232}Th, ^{235}U and ^{238}U.) While some of the potassium (around 50% of the original value) would be leached away from the rocky mantle, the rest would participate in these gradient generating reactions. Following the method of Bouquet *et al.* (2017) and using experimental yields (Spinks and Woods, 1990) with ordinary chondrite concentrations for the radioisotopes, we calculate an expected contemporary production of 0.017 nanomoles/year of H_2 per liter of water (which would be a modest but non-negligible addition to H_2, potentially produced by serpentinization reactions), 0.02 nanomoles/year/L of H_2O_2, and 0.04 nanomoles/year/L of OH. The potassium leached from the rock and dissolved into the ocean could still have served as a source of oxidative power to a largely anaerobic ecosystem, as was proposed for Earth (Draganić *et al.*, 1991).

Generally, throughout Earth's history, the production of redox gradients driven by radiolysis appears to be a small but significant source of energy for subsurface microbial life. In the deep fractured crust, ancient waters are isolated from Earth's surface processes (Holland *et al.*, 2013), including cycling of photosynthetic carbon, photosynthetic oxygen, and other related oxidized nutrients such as sulfate and nitrate. Radiolysis is an important energy source in subsurface environments on Earth, as it maintains redox gradient availability to support microbial life. On early Ceres, radiolysis could augment other chemical redox available and could maintain habitability of such environment long after the initial chemical gradients would have been exhausted (Onstott *et al.*, 1997; Pedersen, 2000; Lin *et al.*, 2005; Onstott *et al.*, 2019).

For example, presently, tens of billions of moles of hydrogen per year are produced globally via radiolysis in continental shield crust alone (Sherwood Lollar *et al.*, 2014). Similarly, in oligotrophic marine sediments, labile organic material is oxidized near the top of the sediment column where it is consumed at the expense of oxygen, nitrate, and sulfate. In the deeper layers of marine sediments with very little organic material infall, microbial communities face a scarcity of viable energy sources, again leaving radiolysis as a significant contributor to those habitats (Blair *et al.*, 2007; D'Hondt *et al.*, 2009; Edwards *et al.*, 2012; Kallmeyer *et al.*, 2012; Parkes *et al.*, 2014). Nevertheless, as remarked nearly 60 years ago by Albert Szent-Gyorgyi, life is molecular electronics—it only works if its spent electrons can find ''a place to rest,'' that is, an electron acceptor (Tien *et al.*, 2012).

The three mechanisms described above (serpentinization in impact-produced melt, upwelling of liquid from the interior, and endogenic radiolysis of water) might have locally provided pairs of electron donor and acceptor species to the present day. In any case, such a hypothetical anaerobic ecosystem would be limited in energy supply (Hoehler and Jørgensen, 2013). Although intuitively this suggests a resulting limitation in the biomass of such possible ecosystems, there is significant variability in measured concentrations of cells (10^2 to 10^8 cells cm^{-3}) sampled at kilometer depths in environments of analogous composition on Earth (Magnabosco *et al.*, 2018; Onstott *et al.*, 2019).

4.5. Origin of Ceres' organics

Marchi *et al.* (2018) hypothesized three possible explanations for the high concentration in organics found on Ceres' surface (see Section 3.3): (1) Ceres formed in an accretional environment different from the carbonaceous chondrites and richer in organics; (2) Ceres hosted conditions amenable to the production of organics from simple compounds expected in an accretional environment in the outer solar system (*e.g.*, CO, CO_2, CH_2O, and HCN); and (3) the high abundance on the surface reflects concentration during Ceres' internal differentiation. This section addresses the fate of accreted organics and the prospect for production of organics inside Ceres. Mechanisms driving the concentration of organics in the crust will be addressed in follow-on studies (*e.g.*, Castillo-Rogez *et al.*, 2019b).

4.5.1. Processing of organics accreted from the protoplanetary disk. The parent bodies of carbonaceous chondrites were environments of organic synthesis and modification likely from interstellar precursors (*e.g.*, Cronin *et al.*, 1988; Kerridge, 1999; Herd *et al.*, 2011; Alexander *et al.*, 2017). Such extraterrestrial organic synthesis might have been important as a source of chemical precursors for the origin of life on Earth (*e.g.*, Anders, 1989; Chyba *et al.*, 1990; Jenniskens *et al.*, 1998; Cooper *et al.*, 2001). The wide range of organics preserved in meteorites, however, is indicative of abiotic reactions, that is, life did not arise on those meteorite parent bodies. However, comparison between carbonaceous chondrites showing increasing degrees of alteration indicates increased organic processing as well (Ehrenfreund *et al.*, 2001; Callahan *et al.*, 2011; Herd *et al.*, 2011; Vinogradoff *et al.*, 2017). Hence, it is plausible that larger water-rich planetesimals, such as Ceres that hosted settings favorable to planetary differentiation, advanced serpentinization, and an ocean could have had more advanced and extensive processing of accreted organics.

On the contrary, observations of carbonaceous chondrites subject to increasing aqueous alteration show the predominance of carbonates over organics (see McSween *et al.*, 2018). This is interpreted as the oxidation of organic compounds to form carbonates. The intimate mixing of organics and carbonates and other products of aqueous alteration found in Ernutet (De Sanctis *et al.*, 2017) may be the expression of this phenomenon. However, owing to Ceres' larger size, the partial pressure of hydrogen was higher. Thus, redox conditions may have differed from those experienced by the smaller carbonaceous chondrite parent bodies, which likely became more oxidized as a result of the easier escape on smaller bodies of any H_2 resulting from water/rock reactions.

4.5.2. Prospect for production of organics inside Ceres. On a young Ceres, several prebiotic pathways are pertinent to an ocean rich in fine silicate particles, as suggested by Travis *et al.* (2018). These may be based on hydrogen cyanide (*e.g.*, Matthews and Minard, 2006; Patel *et al.*, 2015) and/or formaldehyde chemistry (*e.g.*, Saladino *et al.*, 2012), as well as surface-catalyzed syntheses on phyllosilicates (*e.g.*, Ertem and Ferris, 1996; Pearson *et al.*, 2002).

Water/rock interaction oxidizes iron-bearing rock, producing H_2 (McCollom and Bach, 2009), which tends to reduce carbon species in neutral fluids. A simplified reaction describing this process is 18n $(Mg)_2SiO_4$ 6 $(Fe,Mg)_2SiO_4$ + 26n H_2O + n CO_2 → 12 $Mg_3Si_2O_5(OH)_4$ + 4 Fe_3O_4 + CnH_{n+2} (adapted from Holm and Andersson, 1995; Sleep *et al.*, 2004). However, complete reduction to CH_4 is slow, and the production of a mixture of H_2 and CH_4 during serpentinization is a common result in natural settings. In fact, months-long, high-temperature experiments seeking to replicate the reactions between carbon-bearing aqueous fluid and (ultra)mafic silicate rock do not systematically achieve equilibrium between carbon species (Mottl and Holland, 1978; Seyfried and Mottl, 1982; McCollom and Seewald, 2001). Except in the presence of catalysts (Horita and Berndt, 1999; Foustoukos and Seyfried, 2004; Glein *et al.*, 2015), equilibrium is also typically not reached in natural settings (Konn *et al.*, 2009), even when screening out biological processes (McCollom and Seewald, 2007).

The extent to which CO_2 and CH_4 could be removed from the system via clathration (Castillo-Rogez *et al.*, 2018) is also unconstrained, and whether this process could have played a major role in shifting the redox conditions of Ceres' early ocean is unknown. Along the path from CO_2 to CH_4, it is possible that reduction stalled at organic compounds of intermediate oxidation state between carbonate and methane (McCollom and Seewald, 2007). The competition for carbon among multiple processes needs to be further studied to confirm the prospect for an *in situ* origin of the aliphatic organics observed at Ceres' surface (De Sanctis *et al.*, 2017).

4.5.3. Prospect for life to arise on Ceres.

A long-term supply of (both endo- and exogenic) bioessential elements in liquid water in subsurface brines inferred from the Dawn observations suggests that Ceres may have been habitable at some point in its history. Terrestrial organisms can grow at temperatures ranging between 261 and 395 K and pressures in excess of 100 MPa (see Pikuta *et al.*, 2007 for an overview of barophilic bacteria; Jones and Lineweaver, 2010; Harrison *et al.*, 2013). Inside Ceres, these pressures are encountered in the outer 170–220 km. Thermal models indicate that at these depths, temperatures in the above range could have prevailed for much of Ceres' history. In these regions deprived of sunlight, the dominant energy sources are chemical. While serpentinization is geologically rapid (*e.g.*, McCollom *et al.*, 2016), it may have been episodically restarted by impact events. In addition, photo- and/or radiolysis may have prolonged subdued redox gradients to the present day (Section 4.4).

In light of a likely scarce long-term energy supply whether life could initiate and persist on Ceres remains uncertain. Recent studies have provocatively argued that life could have been present on Ceres (Houtkooper, 2011; Sleep, 2018), having emerged *in situ* and/or been transported throughout the inner solar system (*e.g.*, Gladman *et al.*, 2005; Warmflash and Weiss, 2005; Worth *et al.*, 2013). In the latter case, however, by the time Earth had a thriving biosphere, Ceres's near-surface environments should have become less suitable for the implantation of transported organisms due to internal cooling. Likewise, the above considerations make it premature to conclude that life could have emerged on Ceres. Consequently, any relationship between Ceres and the emergence of life on Earth remains speculative.

If life was ever present on Ceres, signs of it might still be detectable today. Among potential biosignatures likeliest to survive to the present day, many lipid biomarkers are stable on billion-year timescales (Georgiou and Deamer, 2014). Others, such as particular biological amino acids (*e.g.*, Dorn *et al.*, 2003), are stable on shorter geologic timescales when frozen in ice (Kanavarioti and Mancinelli, 1990). Nucleic acid chains are recoverable only up to about 1 Ma from ice and permafrost (Willerslev *et al.*, 2004). Because Ceres is airless, the lifetime of all potential chemical biosignatures in near-surface material could be significantly further shortened due to radiation (Pavlov *et al.*, 2012).

5. Summary and Path Forward

The Dawn mission has revolutionized our understanding of Ceres in the same decade that has also seen the rise of ocean worlds as a research and exploration focus. Arguably, the most significant finding from the Dawn mission is unambiguous evidence for extensively, aqueously altered material on Ceres' surface, as well as features indicative of recent cryovolcanism. Furthermore, the globally homogeneous distribution of that material suggests production in an ocean, presumably early on in Ceres' history before internal differentiation (Ammannito *et al.*, 2016; Park *et al.*, 2016).

Dawn's observations confirmed earlier predictions for a volatile-rich crust encompassing the bulk of a former ocean, now frozen, and provide hints for a weak interior that may reflect the presence of a relict liquid layer or brine pockets. These observations led to Ceres' classification as a ''candidate'' ocean world in the ROW (Hendrix *et al.*, 2019). Current knowledge indicates that Ceres once had water, organic building blocks for life, energy sources, and redox gradients, and perhaps still does today. Perhaps more importantly, Ceres' astrobiological value comes from its potential for continuous habitability, commencing directly after accretion with a global ocean in which advanced chemical differentiation developed.

This global ocean could have been maintained for billions of years (Travis *et al.*, 2018). Most of Ceres' surface properties record the consequences of that early period, while contemporary activity is evident in a few places. However, as per its size and water abundance, Ceres belongs to a class of objects that could host a high fugacity of hydrogen, organic molecules, and alkaline conditions, as was suggested for Europa (*e.g.*, McKinnon and Zolensky, 2003) and inferred from Cassini observations of Enceladus (Postberg *et al.*, 2011; Marion *et al.*, 2012).

Future exploration of Ceres would reveal the degree to which liquid water and other environmental factors may have combined to make Ceres a habitable world. Confirmation of the existence of liquid inside Ceres at present, and assessment of its extent, is the natural next step when following the ROW (*Goal II, A.1*, see Table 1 and Hendrix *et al.*, 2019). Another key question for any coming mission is whether there exist oxidants at the surface to help the emergence of life or at least its habitability (*Goal III, A.1*). A favorable redox discovery would deepen the case for Ceres meeting our current definition of habitability. Another topic of major importance is about quantifying the abundance, sources and sinks, and chemical forms of CHNOPS elements (*Goal III, B.2*), assessing the inventory and determining the origin(s) of organic compounds beyond the limited observations of Dawn, and determining their origin(s) (*Goal III, B.1*).

In addition to future exploration, progress in our understanding of Ceres would also benefit from work on terrestrial and laboratory analogues. While the role of brines in driving activity on volatile-rich bodies was recognized early on, the experimental data on the thermophysical properties of brines, hydrated salts, ammonium salts, and clathrates currently available are inadequate to support precise modeling of these bodies. Emerging ideas in planetary science, such as the effect of radiolysis in the creation of redox gradients in ocean worlds, also require experimental research to be pursued in greater detail, for example, to understand the efficiency of this process in producing oxidants and creating local habitable zones.

Finally, Ceres could be a representative endmember for Ocean Worlds that are not tidally heated and that accreted ammonia as in Callisto and potentially also Pluto (Nimmo *et al.*, 2016). The prospect for a body heated only by radioisotopes to retain liquid until present is not simply a function of size; it depends on the redistribution of radioisotopes upon geochemical transfers, as well as the types of salts generated in early hydrothermal environments or brought in by accreted planetesimals. Further exploration of Ceres to assess the state of remaining liquid (extent and composition) would in turn indicate which classes of bodies (physical properties and origin) are more likely to preserve relict oceans until present. Ceres is thus a key piece of the overall puzzle of ocean world evolution.

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Abbreviations Used

CI = The Ivuna chemical group of carbonaceous *chondrites*
CM = The Mighei chemical group of carbonaceous *chondrites*
GRaND = gamma ray and neutron detector
HST = *Hubble Space Telescope*
N/A = Not Applicable
ROW = Roadmap for Ocean Worlds
VIR = visible and infrared spectrometer